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Performance of a Virtual Tall Tower (VTT) approach for estimating CO₂ concentrations in the mixed layer from eddy covariance measurements near the surface

Lediane Marcon-Henge¹, Alexander Graf¹, and Matthias Peichl²

¹Forschungszentrum Jülich, Institute of Bio- and Geosciences: Agrosphere (IBG-3), Landau, Germany (l.marcon@fz-juelich.de)

²Swedish University of Agricultural Sciences, Department of Forest Ecology and Management, Umeå, Sweden

Atmospheric CO₂ measurements provide essential constraints for carbon-budget estimates and atmospheric modelling. Virtual tall tower (VTT) methods are a promising, but yet underexamined approach for upscaling ecosystem-level CO₂ concentrations measured at eddy covariance (EC) sites (typically 2–50 m above ground) to atmospheric measurements representative of tall towers (TT; ~100 m and higher). Implementing VTT approaches at existing EC stations could therefore expand the currently sparse network of TT observations. In this study, we evaluate the applicability of a VTT approach using collocated EC–TT measurements. We use 2024 data from the combined ecosystem-atmosphere station Svartberget site in northern Sweden (SE-Svb, SVB), part of the ICOS (Integrated Carbon Observation System) network, with brief examples from one or more other sites. A key advantage of the ICOS Svartberget station is that ecosystem EC and atmospheric TT measurements are available at the same location, with EC observations at 35 m and TT measurements at 35 m and 150 m. The 35 m TT measurements are an important asset for post-hoc calibration correction of the concentrations measured by the EC system, since state-of-the-art EC stations typically do not meet the high calibration requirements of a TT measurement. We implemented the VTT method proposed by Haszpra et al. (2015) and tested the gradient functions of Patton et al. (2003) and Wang et al. (2007) to define a base-run configuration. We then performed a sensitivity analysis of key variables in the VTT formulation. Model performance was evaluated using bias, root mean square error (RMSE), and correlation, by comparing VTT-estimated CO₂ concentrations at the TT top height (150 m) against measured TT concentrations. For 2024, approximately 30% of valid hourly data points met the well-mixed criteria required for VTT application. When treating EC calibration and VTT calculations as separate steps, EC calibration exerted the largest influence on estimated CO₂ at TT height, highlighting calibration as a critical prerequisite for reliable mixed-layer concentration estimates. Sensitivity analysis further showed that, when accounting for both numerical perturbations and measurement uncertainty, the planetary boundary layer height was the most influential variable, producing the largest changes in performance statistics relative to the target TT concentrations. Taken together, these results suggest that VTT approaches could increase the coverage of TT-representative atmospheric CO₂ estimates. Improving planetary boundary layer height (PBLH) estimates should further increase

VTT accuracy. Further steps, VTT performance should be tested across additional sites and time periods to assess robustness under different conditions.